# Comparison of SSM/I-derived Sensible and Latent Heat Fluxes and Aircraft-measured Turbulent Heat Fluxes Over the Japan/East Sea During Cold Air Outbreaks

Bernard A. Walter
Northwest Research Associates
P. O. Box 3027
Bellevue, WA 98009
phone: (425) 644-9660, x-320; fax: (425) 644-8422; e-mail: walter@nwra.com

Award #: N00014-00-M-0061
http://www.onr.navy.mil/sci_tech/ocean/onrpgabv.htm

## LONG TERM GOALS

To develop a methodology for estimating latent and sensible heat fluxes from the ocean using satellite remote sensing data.

## OBJECTIVES

The objectives are:

- to use algorithms developed for estimating latent and sensible heat fluxes from SSM/I data during cold air outbreaks over the Labrador Sea to make similar flux estimates for the Japan/East Sea (JES) during the ONR JES field program in February 2000; and,

- to compare the SSM/I flux estimates to in situ area-averaged turbulent sensible and latent heat flux measurements made by an instrumented aircraft over the JES by Dr. Carl Friehe during the ONR Japan/East Sea field program.

## APPROACH

The algorithms developed during the Labrador Sea program use SSM/I brightness temperature data to provide areal estimates of surface wind speed, and integrated water vapor (IWV). Relationships were then developed between the IWV estimates and the surface mixing ratio and also surface air temperature using in situ data data from the Labrador Sea field program. With this information, and a value of the sea surface temperature, we then use the bulk flux formulations to estimate values of both the latent and sensible heat fluxes.

Here we compare the flux estimates obtained from the SSM/I algorithms to low level turbulent flux measurements made by Dr. Carl Friehe using the instrumented CIRPAS Twin Otter aircraft as part of the Winter 2000 Japan East Sea (JES) experiment. The aircraft was instrumented with wind, temperature, humidity, IR sea surface temperature and aircraft motion and navigation sensors. Data were recorded at a rate of 40 Hz for turbulent eddy correlation flux calculations.

Thirteen research flights were flown from Misawa NAF, Japan over the JES in cold air outbreak conditions on: January 30 and 31; February 2, 8, 9, 11, 14, 16, 17, 20, 21, 24 and 27. The purpose of the flights was to measure the surface fluxes and their spatial variability during cold air outbreak conditions. Here we compare the aircraft surface fluxes with those estimated from the SSM/I data for one of the flights in order to assess the accuracy of the SSM/I technique.

We use individual swath SSM/I brightness temperature data from the F13 DMSP satellite during the time period of the experiment at times closest to the aircraft measurements. The Labrador Sea algorithms were originally developed using the F13 data so we felt that the comparisons would be more valid if we used data from that satellite for the JES calculations. There is both a local morning and evening pass from the satellite.

The brightness temperatures were extracted at the locations of the aircraft flux measurements for each of the flights. The data set was screened for bad and missing data. These brightness temperatures were then used to calculate values of surface wind speed and IWV, and then from these, values of ($q_s$ - $q_a$) (the difference in the saturation and actual mixing ratio at the surface) and $T_a$, the surface air temperature, over the JES using the Labrador Sea algorithms.

## WORK COMPLETED

The results reported in this section are modified somewhat from those reported in last year's annual report due to further analysis of the SSM/I data sets. Thus Tables 1 and 2 are repeated here.

Turbulent flux data collected by the CIRPAS Twin Otter obtained from Dr. Carl Friehe at the University of California-Irvine for a flight on February 17-18 have been compared to fluxes from the SSM/I data during the JES field program. This flight was an internal boundary layer growth pattern that included eleven low-level crosswind flux runs going downwind across the Japan East Sea. The first run was at 42.218 deg N, 132.146 deg E. The final run was at 37.541 deg N, 137.791 deg E. The magnitude of the total (sensible plus latent) heat flux varied from a minimum of 175 to a maximum of 443 W/m$^2$.

SSM/I brightness temperature swath data from the F13 satellite for February 17-18 was extracted over the JES from tapes received from Remote Sensing Systems (RSS), Inc. Two satellite passes were available that essentially bracketed the flight time period. One pass was on February 17 at 1200 UTC and the second on February 18 at 1200 UTC. The flight was at 00-04 UTC on the 18$^{th}$.

The SSM/I brightness temperatures were used to generate maps of surface wind speed and integrated water vapor (IWV). Table 1 shows the average wind speed measured by the aircraft at each stack pattern and the average wind speed computed from the brightness temperatures from both of the SSM/I passes bracketing the time of the flight. Also shown for comparison is the average wind speed computed using the algorithm published by Goodberlet et al. (1989).

The values of the integrated water vapor (IWV) (not shown) from both the Labrador Sea algorithm and that given in Goodberlet et al (1989) were nearly identical. We next computed: values of ($q_a$ – $q_s$), the predicted values of the surface air temperature, and finally the surface sensible and latent heat fluxes using the SSM/I algorithms and compared these to the aircraft measured fluxes. These comparisons is shown in Table 2.

***Table1. Comparison of the aircraft measured wind speeds with SSM/I-derived wind speeds using both the Labrador Sea and the Goodberlet et al. (1989) algorithms for February 17-18, 2000.***

| Stack | Latitude, Deg N. | Longitude, Deg E. | Speed, m/s | Direction, deg | Average SSM/I speed, m/s Lab Sea algorithm | Average SSM/I speed, m/s Goodberlet et al. algorithm |
|---|---|---|---|---|---|---|
| 1 | 42.22 | 132.15 | 13.3 | 336 | 5.5 | 9.5 |
| 2 | 41.69 | 132.83 | 15.9 | 324 | 8.5 | 12.2 |
| 3 | 41.22 | 133.45 | 16.5 | 315 | 7.5 | 11.2 |
| 4 | 40.74 | 134.05 | 14.1 | 306 | 9.0 | 12.5 |
| 5 | 40.28 | 134.62 | 12.8 | 303 | 9.1 | 12.9 |
| 6 | 39.82 | 135.18 | 12.2 | 305 | 9.7 | 12.9 |
| 7 | 39.37 | 135.71 | 12.1 | 300 | 9.4 | 13.0 |
| 8 | 38.90 | 136.24 | 11.8 | 303 | 10.3 | 13.8 |
| 9 | 38.43 | 136.79 | 13.5 | 293 | 9.3 | 13.1 |
| 10 | 37.96 | 137.32 | 13.2 | 305 | 9.7 | 13.7 |
| 11 | 37.54 | 137.70 | 14.3 | 306 | 10.6 | 16.4 |

***Table 2a. Comparison of values of aircraft-measured and SSM/I-estimated: air temperature, latent heat flux and sensible heat flux using the Labrador Sea algorithms. (* = outlier removed)***

| Stack | **Aircraft** measured **air temperature**, Deg C | **SSM/I** estimated **air temperature**, Deg C | **Aircraft** measured **sensible heat flux**, $W/m^2$ | **SSM/I** estimated **sensible heat flux**, $W/m^2$ | **Aircraft** measured **latent heat flux**, $W/m^2$ | **SSM/I** estimated **latent heat flux**, $W/m^2$ |
|---|---|---|---|---|---|---|
| 1 | -8.8 | -7.9 | 123 | 56 | 111 | 44 |
| 2 | -7.8 | -6.1 | 178 | 69 | 172 | 67 |
| 3 | -6.6 | -6.1 | 104 | 79 | 113 | 74 |
| 4 | -5.5 | -4.9 | 84 | 82 | 91 | 87 |
| 5 | -4.6 | -4.9 | 116 | 102 | 136 | 105 |
| 6 | -3.9 | -2.9 | 117 | 79 | 116 | 100 |
| 7 | -2.9 | -3.8 | 164 | 130 | 200 | 137 |
| 8 | -1.5 | -3.6 | 114 | 130 | 165 | 140 |
| 9 | -0.8 | -3.8 | 183 | 150 | 260 | 154 |
| 10 | +0.5 | -3.1 | 136 | 158 | 282 | 167 |
| 11 | +1.2 | -4.7* | 149 | 198* | 198 | 191* |

***Table 2b. Comparison of values of aircraft-measured and SSM/I-estimated: air temperature, latent heat flux and sensible heat flux using wind speeds and IWV from the Goodberlet et al. (1989) algorithm. (* = outliers removed)***

| Stack | **Aircraft** measured **air temperature**, Deg C | **SSM/I** estimated **air temperature**, Deg C | **Aircraft** measured **sensible heat flux**, W/m$^2$ | **SSM/I** estimated **sensible heat flux**, W/m$^2$ | **Aircraft** measured **latent heat flux**, W/m$^2$ | **SSM/I** estimated **latent heat flux**, W/m$^2$ |
|---|---|---|---|---|---|---|
| 1 | -8.8 | -8.2 | 123 | 100 | 111 | 76 |
| 2 | -7.8 | -6.3 | 178 | 103 | 172 | 97 |
| 3 | -6.6 | -6.3 | 104 | 121 | 113 | 111 |
| 4 | -5.5 | -5.1 | 84 | 117 | 91 | 122 |
| 5 | -4.6 | -5.3 | 116 | 151 | 136 | 150* |
| 6 | -3.9 | -3.1 | 117 | 109 | 116 | 134 |
| 7 | -2.9 | -4.2 | 164 | 186 | 200 | 191 |
| 8 | -1.5 | -3.9 | 114 | 180 | 165 | 191 |
| 9 | -0.8 | -4.2 | 183 | 220 | 260 | 220 |
| 10 | +0.5 | -3.5 | 136 | 233 | 282 | 239 |
| 11 | +1.2 | -6.2 | 149 | 341* | 198 | 306* |

The values of the SSM/I wind speeds, air temperatures and fluxes shown in Tables 1 and 2 were obtained by averaging, for each of the two SSM/I passes used, values closest to the aircraft leg, and then averaging the two pass values since the two passes bracketed the actual time of the aircraft flight. When there were several pixels surrounding the exact location of the aircraft stack the values of the SSM/I variable used was a weighted average from the two or three pixels closest to the aircraft stack.

## RESULTS

The speed values from the Labrador Sea algorithm were very low (Table 1) over the whole aircraft flight pattern. The values from the Goodberlet et al (1989) algorithm were lower for the first few points but fairly close thereafter.

The SSM/I algorithm used to estimate air temperature from IWV was derived using a data set that had a relatively limited range of temperatures. There were only 3 positive temperatures in the Labrador Sea data set. These were 0.5, 0.8 and 1.9 deg C. The functional fit chosen was an exponential and the asymptotic values as IWV gets large is < 2 deg C. This is why the temperature estimates from the IWV values derived from the SSM/I data for temperatures warmer than about -4 deg C are so low. The use of a larger range of temperature values and a different functional fit to the data would probably result in better air temperature predictions. This work though is beyond the scope of the present project.

### A. HEAT FLUX ESTIMATES FROM THE LABRADOR SEA ALGORITHM

The sensible heat flux estimates (Table 2) are very low over the first part of the aircraft track due to the very low wind speed estimates, and were higher over the latter part of the leg due to the low air temperature estimates. The average value of sensible heat flux over the entire flight track was 111 W/m2 whereas the measured value was 133 W/m2.

The latent heat flux estimates from the Labrador Sea algorithm are significantly lower than the measured values over the whole flight track. This is due primarily to the very low wind speed estimates from the Labrador Sea algorithm. The average value of the SSM/I estimated latent heat flux over the entire flight track was 115 W/m2 and the measured value was 167 W/m2.

B. HEAT FLUX ESTIMATES USING THE GOODBERLET ET AL (1989) ALGORITHM

The sensible heat flux estimates were relatively close to the measured values over the first half of the flight track with the differences due to a combination of wind speed and air temperature estimate differences. The sensible heat flux estimates over the latter half of the track are larger due to the low air temperature estimates. The average value over the entire track (166 W/m2) is larger than the measured value (133 W/m2) due to this latter factor.

Latent heat flux estimates vary along the aircraft track between under and over estimates. On average over the entire flight track the SSM/I estimate (165 W/m2) is nearly identical to the measured value ( 167 W/m2).

From the above comparisons with in situ aircraft measurements it is clear that the Labrador Sea algorithms are not adequate for accurately estimating either latent or sensible heat fluxes from SSM/I data over the Japan East Sea. The deficiencies lie principally in: the very low wind speed estimates; and in the air temperature estimates. Significant errors in the air temperature estimates for values warmer than about -4 deg C. contribute large errors to the sensible heat flux estimates. This is probably due to the fact that such a limited data set was used to develop the algorithm.

The results also show that if the Goodberlet et al (1989) algorithm is used to calculate wind speed and IWV and these values are used to estimate sensible and latent heat flux, the estimated values are much closer to the measured values. This is especially true for the latent heat flux. Differences in the sensible heat flux estimates can be explained primarily by the deficiency in the air temperature algorithm. Development of a new functional form of the algorithm using an expanded data set (i.e., both the original Labrador Sea data together with the JES aircraft data) may result in better estimates of sensible heat flux by the SSM/I algorithm.

The comparisons with the aircraft measurements also show that pixel by pixel estimates of fluxes are really not feasible due to a number of factors. An important factors is that the aircraft measurements are relatively instantaneous (over several minutes time), whereas the satellite estimates are made by averaging data from two satellite passes bracketing the time of the aircraft data collection (+/- 6 hours or so). On the other hand when the measured fluxes are averaged over the entire flight track (100's of kilometers) and compared with the satellite estimates averaged over a similar spatial domain the comparisons are quite reasonable

Flux measurements made by the Twin Otter on other flights during the JES have been obtained from Dr. Carl Friehe at the University of California-Irvine. The additional flights were on January 30-31 and January 31-February 1 and February 2-3 and 21-22. Results from the comparisons between the aircraft fluxes and SSM/I flux estimates are qualtitatively similar to those for the February 17-18 flight. Detailed results will be reported in the final report to be submitted for this project.

As a final comment, the original work by Liu (1984; 1986) showed that over periods longer than a few weeks mean precipitable water was an adequate predictor of $q_a$. Also in the work of Jourdan and Gautier (1995) relating $T_a$ to IWW, they used monthly averages of $T_a$ and IWV in developing the relationship between these two quantities. Our attempt here to use these relationships both spatially in a mesoscale sense and temporally on a nearly instantaneous basis may just be expecting too much of the data. There may be just too much inherent variability in the data to expect these relationships to hold on such small spatial and temporal scales.

## IMPACT/APPLICATIONS

If this method of remotely estimating surface turbulent sensible and latent heat flux fields proves robust it would provide a method for supplying data for initializing oceanographic numerical models, and for the analysis/interpretation of oceanographic measurements. Having these higher resolution (~50 km) flux fields is critical for studying the scales of oceanographic processes important for ocean convection in the JES.

## RELATED PROJECTS

As noted above, this work is closely related to the analysis of the Twin Otter turbulent flux data being carried out by Dr. Carl Friehe at the University of California-Irvine.

## REFERENCES

Goodberlet, M., C. Swift, J. Wilkerson, Remote sensing of ocean surface winds with the Special Sensor Microwave/Imager, *J. Geophys. Res., 94*, 14547-14555, 1989.

Liu, W., Estimation of latent heat flux with SEASAT-SMMR, a case study in the N. Atlantic. Large-Scale Oceanographic Experiments and Satellites. C. Gautier and M. Fieux, eds., D. Reidel, 205-221, 1984.

Liu, W., Statistical relation between monthly mean precipitable water and surface-level humidity over global oceans, Mon. Wea. Rev., 114, 1591-1602, 1986.

Jourdan, D. and C. Gautier, Comparison between global latent heat flux from multisensor (SSM/I and AVHRR) and rom in situ data, *J. Atmos. Ocean Technol., 12*, 46-72, 1995.

Miller, D. and K. Katsaros, Satellite-derived surface latent heat fluxes in a rapidly intensifying marine cyclone, *Mon. Wea. Rev., 120*, 1093-1107, 1992.

Schulz, J., P. Schluessel, and H. Grassl, Water vapor in the atmospheric boundary layer over the oceans from SSM/I measurements, *Int J. Rem. Sensing, 14*, 2773-2789, 1993.